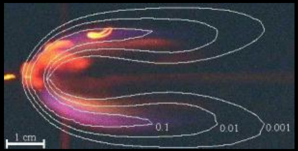
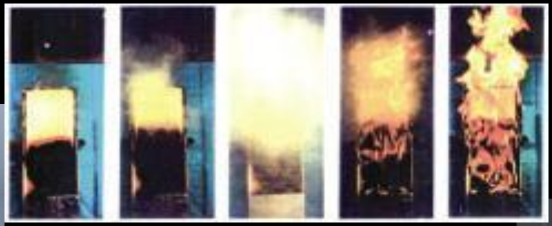
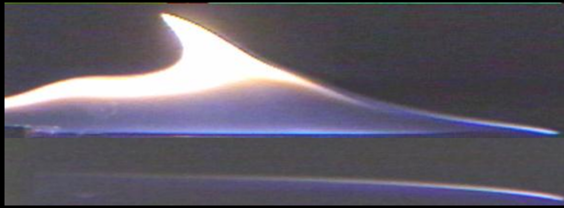
Burning Questions in Gravity-Dependent Combustion Science



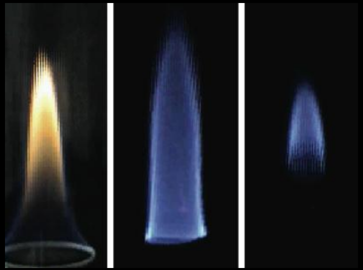




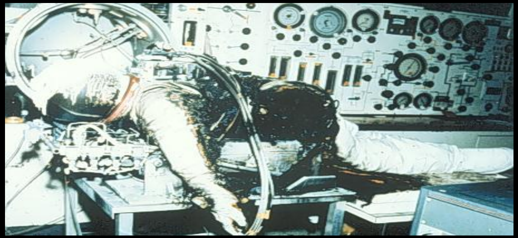




November 28, 2012





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Combustion Relevance

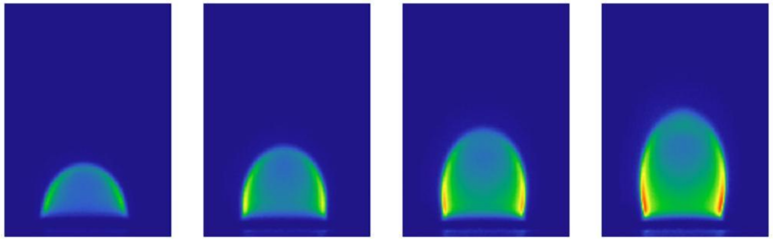
Combustion is:

- Our primary energy source (85%)
- The primary cause of global warming,
- The primary cause of air pollution—affects people directly every day,
- An inherent part of many industrial processes
- A major source of the loss of property and life,
- The power source for portable applications
- A catastrophic hazard for the manned space flight program,
- A major source of new materials (nano-tubes, diamond, ceramics etc.),
- Arguably man’s first technology but also remarkably complex.

The biggest challenge to the discipline is that combustion has been so pervasive for so long in everyday life that people mistakenly believe it is well understood. The reality is that substantial improvements in the quality of life in space or here on earth will require improvements in our ability to predict and control combustion.

Terrestrial issues where microgravity combustion can have impact

- **Energy**
  - **High-efficiency, low-emission flames can be near limit, which are unstable, where kinetics are important**
- **Environment (e.g., global warming)**
  - **Carbon sequestration**
    - **High oxygen flames**
      - **Oxy-fuel flames**
      - **Integrated Gasification Combined Cycle (IGCC)**
  - **Reduced CO_2 through use of fuels that are high in H_2**
    - **Need for improved understanding of transport and instability**
  - **Soot control and reduction**
- **Combustion Technology**
  - **Electric field control of flames**
- **Hydrogen safety (alternative fuels)**
- **Mine safety-premixed systems**
- **Fire Safety**



Ground-based results: Flame Spread

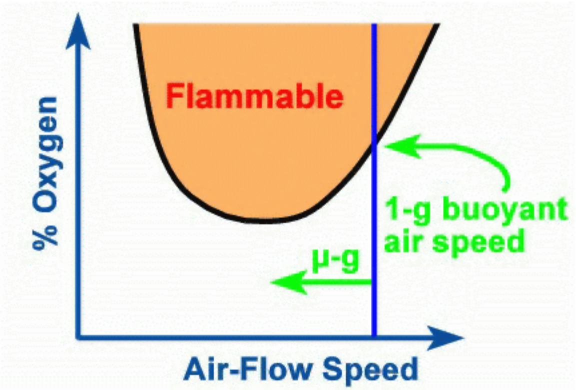
Demonstration of the significance of low speed air flows on material flammability.

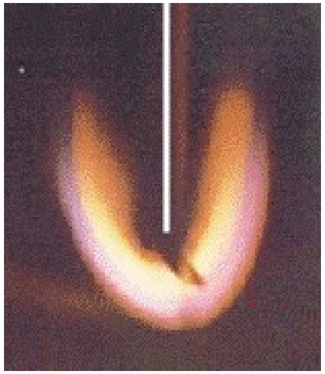
Demonstration of the non-monotonic dependence of flame spread on gravity level. Intermediate gravity levels may be the most hazardous.

Observation that material ignitability can increase at reduced pressure.

Demonstration that flame spread behavior in low-gravity is substantially different from 1-g

Invalidation of the prevalent assumption that 1-g is always a worse case than low-g

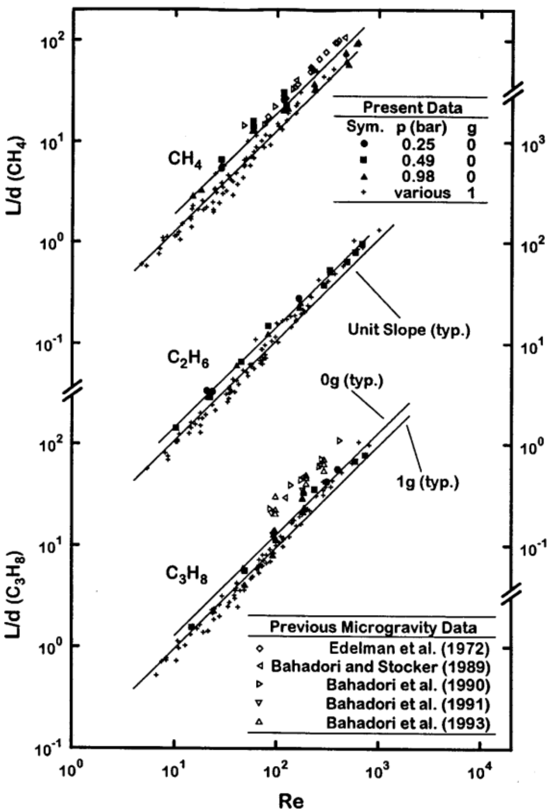


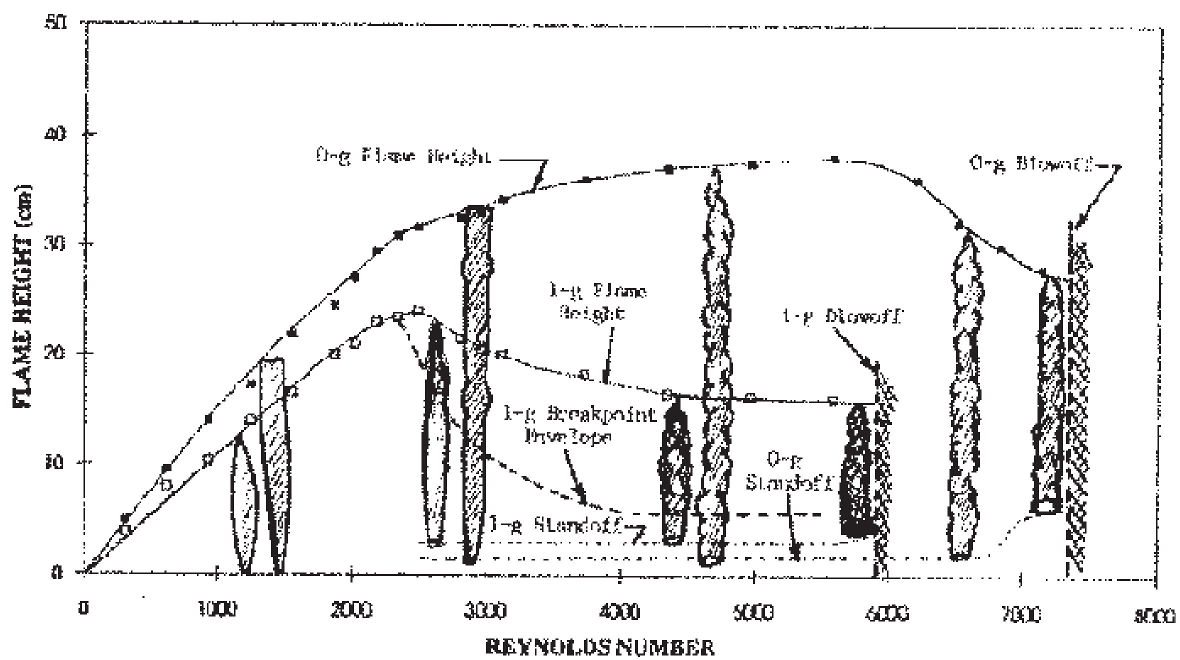


Ground-based results: Non-Premixed Systems

Experimental demonstration of the intrusion of buoyancy on flame structure even at high Froude numbers.

Simple flame shape models have now been validated by ground-based microgravity testing providing classical data for the text books of the future.





Pre-ISS Flight Experiment History

Condensed Fuel Flame Spread/Burning Rate Experiments

– SSCE (1990-1998)	Middeck	Flame Spread
– WIF, FFFT, RITSI, OFFS, FFFT-Mir (1992-1997)	Glovebox	Flame Spread
– CFM, CFM-Mir (1992-1996)	Glovebox	Candles
– SCM, MSC (1992-2000)	Glovebox /GAS	Smoldering
– DARTFIRE, SAL (1994-1998)	Sounding Rocket	Flame Spread

Droplet Combustion

– DCE(1997)	Spacelab
– FSDC 1, 2 (1995-1997)	Glovebox

Gaseous Non-premixed (Gas Jets)

– LSP(1997, 2003)	Spacelab/Hab
– ELF(1997)	Glovebox,
– TGDF (1997)	GAS

Gaseous Premixed

– SOFBALL(1997, 2003)	Spacelab/Hab

Fire Safety

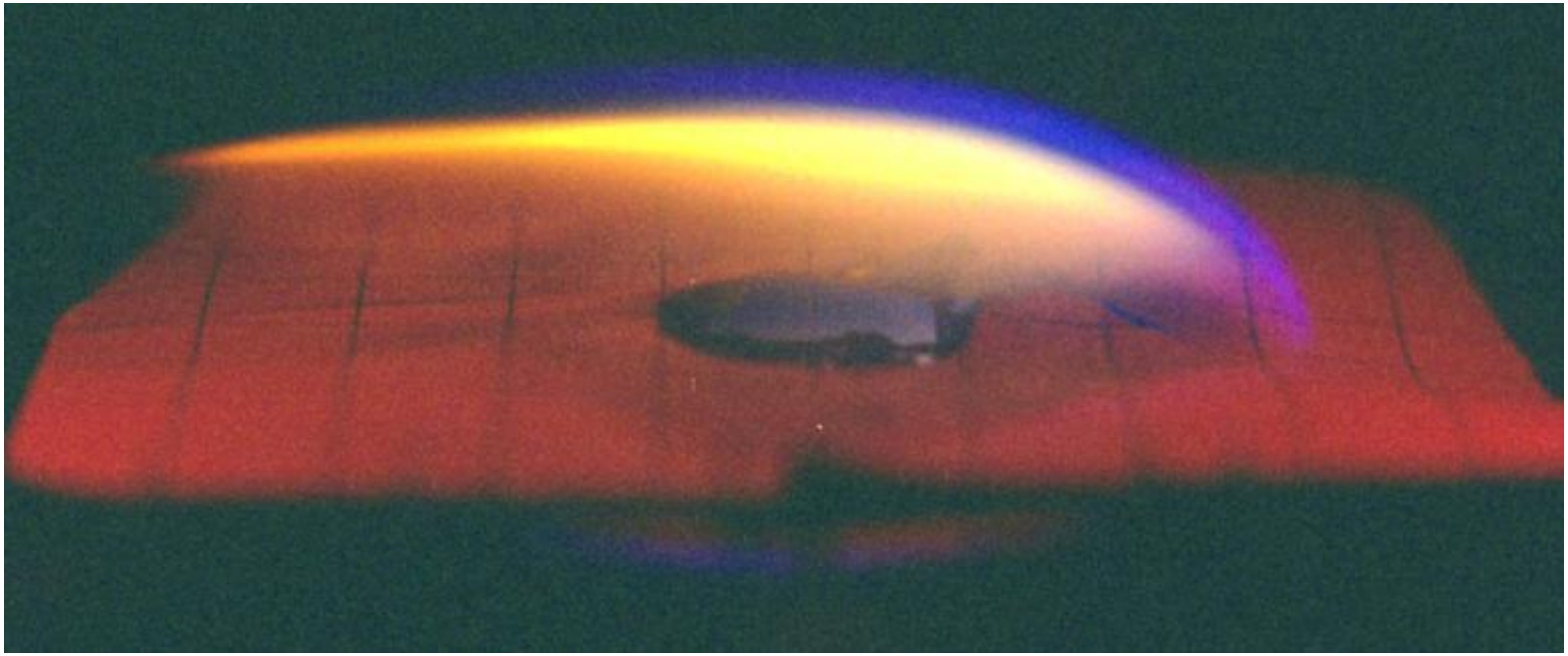
– CSD (1996)	Glovebox
– MIST (2003)	SpaceHab

Flight results: Flame Spread

Ignition at the middle of the sample:

- **Flame spreads upstream.**
- **This is completely contrary to normal gravity**

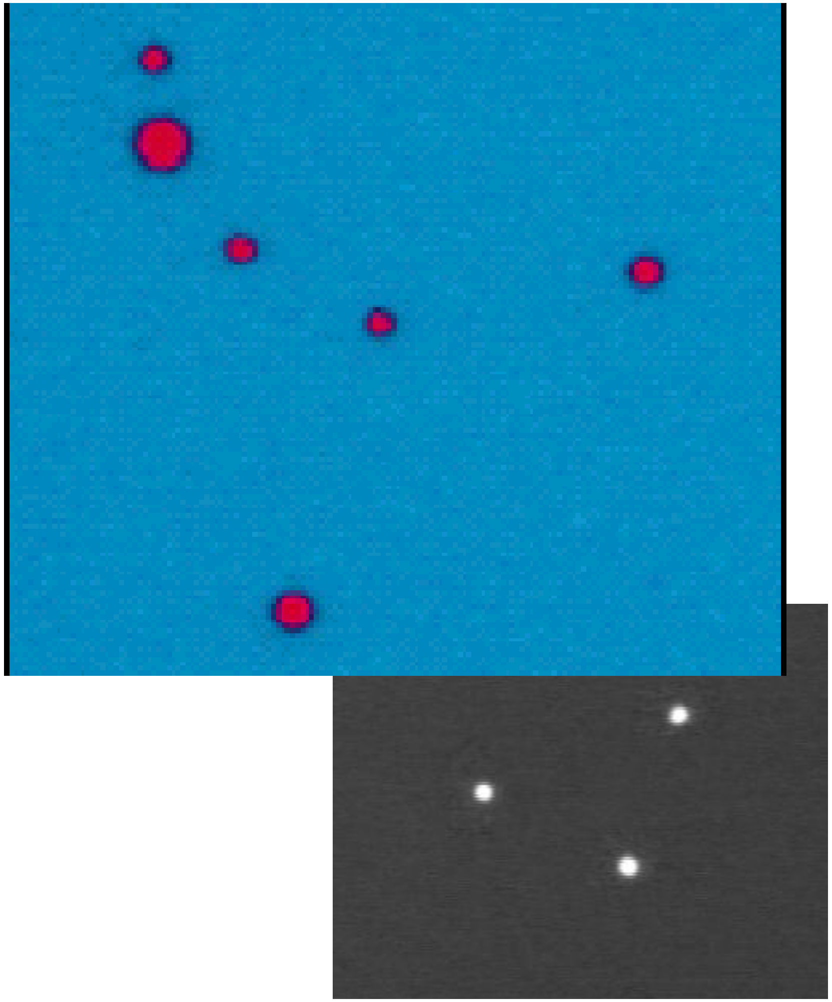
Air Flow



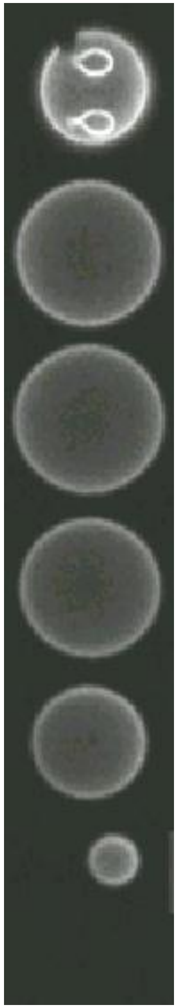
Flight Results: Premixed Flames

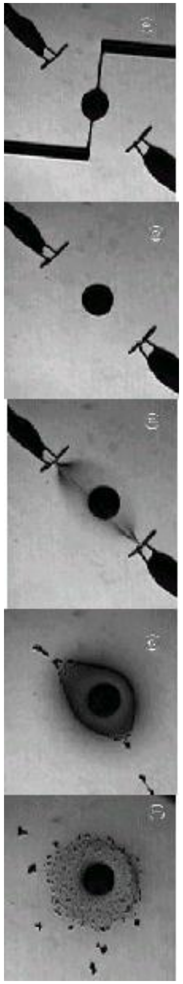
Flame Balls

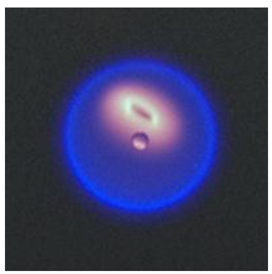
- **Unique combustion phenomena**
- **Hypothetically predicted**
- **Impossible to observe in 1-g**
- **"Premixed Diffusion Flame"**
- **Weakest flames ever burned ~1 Watt**
- **Demonstrated weaknesses in kinetic submodels**
- **Much steadier than expected (~ 1 orbit)**
- **G-sensitivity greater than anticipated..**



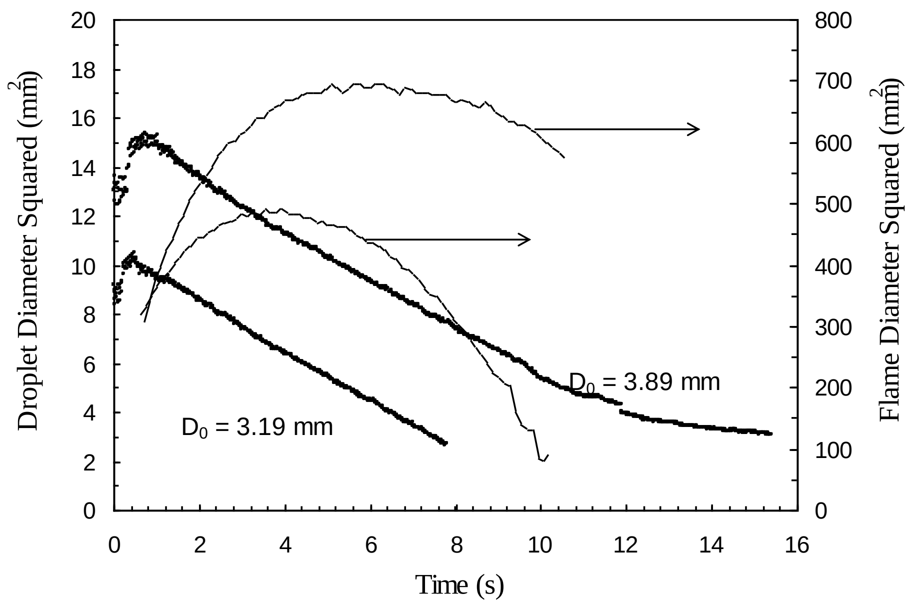
Droplet Combustion







39% (of total US energy) is from liquid fuels
(97% of transportation energy is liquid fuels)
• Droplet experiments provide an idealized geometry to develop fundamental experimental data to validate detailed chemical kinetic models



Heptane droplet burning at atmospheric pressure in 30-70 O_2-He mole fraction environment

Diffusion Flames / Soot

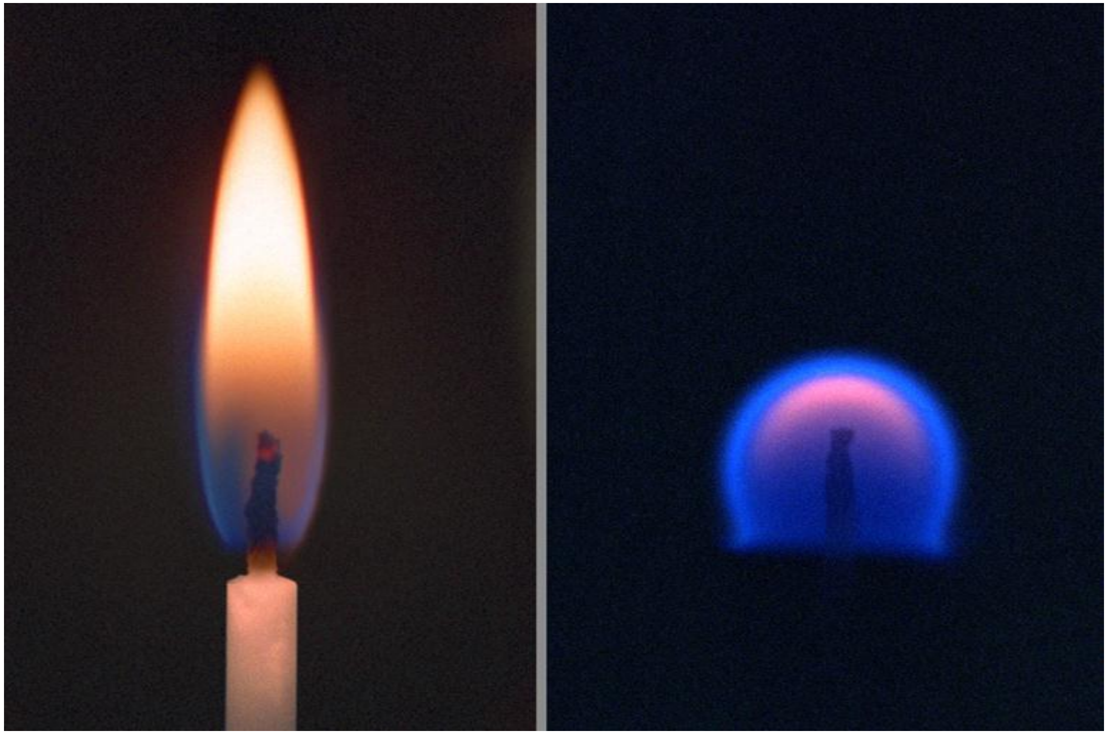
CANDLE FLAMES

Classical diffusive combustion system

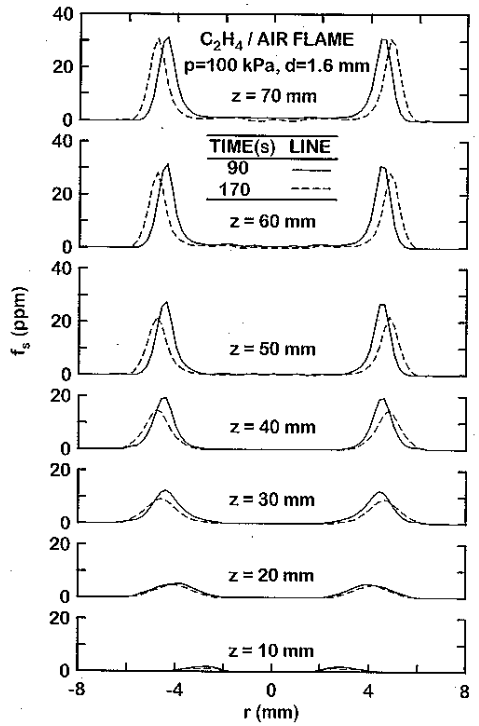
Excellent tutorial for the public

Challenging system for detailed modeling

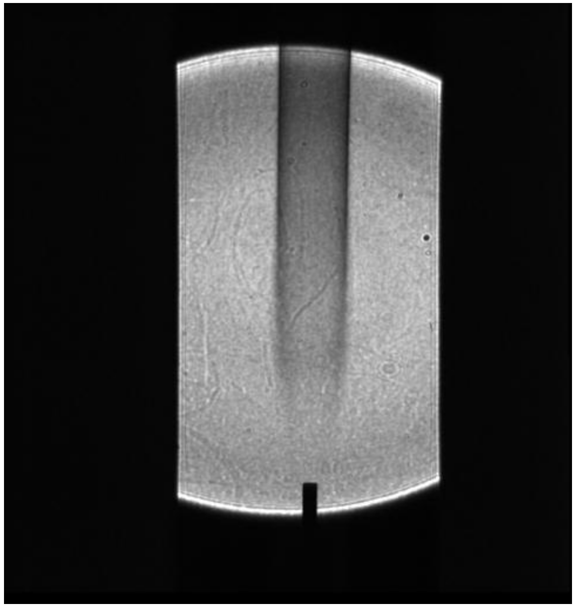
Demonstrated the long term viability of diffusion flames on condensed fuels



Flight results: Diffusion Flames / Soot



- Soot measurements in non-buoyant flames supporting model development
- Smoke points found in low-gravity contrary to predictions in literature.



Combustion Science - ISS Experiments

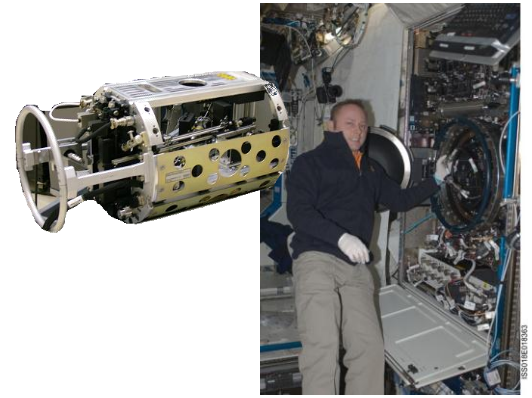
- **Gaseous Combustion**
  - Dust and Aerosol measurement Feasibility Test (DAFT) – 2006, MSG
  - Smoke Aerosol Measurement Experiment, and Reflight (SAME, SAME-R) – 2007, 2010 MSG
  - Smoke Point in Coflow Experiment (SPICE) – 2009, MSG
  - Structure and Liftoff in Combustion Experiment (SLICE) – 2012, MSG
  - Advanced Combustion via Microgravity Experiments (ACME) –CIR
- **Liquid Combustion**
  - Multi-User Droplet Combustion Apparatus (MDCA)/FLame Extinguishment eXperiment (FLEX) – 2009-2012, CIR
  - FLame Extinguishment eXperiment-2 (FLEX-2), CIR, with JAXA & ISA
- **Materials Combustion**
  - Burning and Suppression of Solids (BASS), 2012, MSG
  - Flammability Assessment of Materials for Exploration (FLAME)
- **Reactive Systems**
  - High Temperature Insert - Reflight (HTI-R/SCWM), DECLIC, CNES-led experiment
- **Fire Safety**
  - Spacecraft Fire Safety Demonstration flight

ISS Results Droplet Combustion

Flame Extinction Experiment (FLEX) – 2009 through 2012

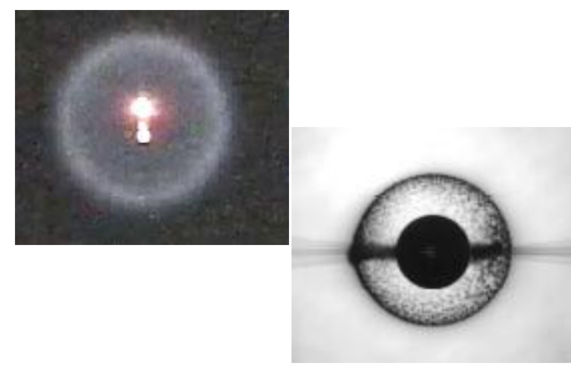
FLEX-2, FLEX-2J, FLEX-ICE-GA – 2012 through 2015

- Spherically-symmetric geometry only achievable in microgravity.
- Extinction test bed
- Kinetic and transport processes
- Over 400 droplets burned to date.



(Left) FLEX Chamber Insert Assembly Apparatus. (Right) Mike Fincke operating the CIR.

- FLEX Fire Extinguishment via inerts
- FLEX-2 extends the studies to consider issues relevant to energy and fuel efficiency by including complexities:
  - Multi-component fuels,
  - Binary droplet arrays
  - Convective airflow
- FLEX-2J is a collaboration with JAXA: linear droplet arrays
- FLEX-ICE-GA is a collaboration with ASI :Surrogate fuels (idealized bio-fuels)



(Left) FLEX Chamber Insert Assembly Apparatus. (Right) Mike Fincke operating the CIR.

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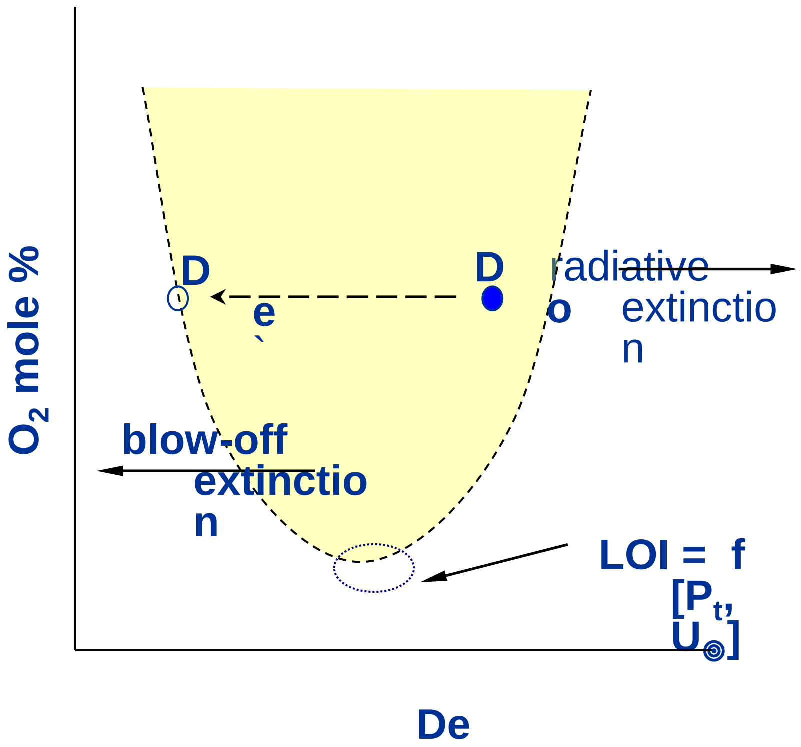
FLEX Investigation results

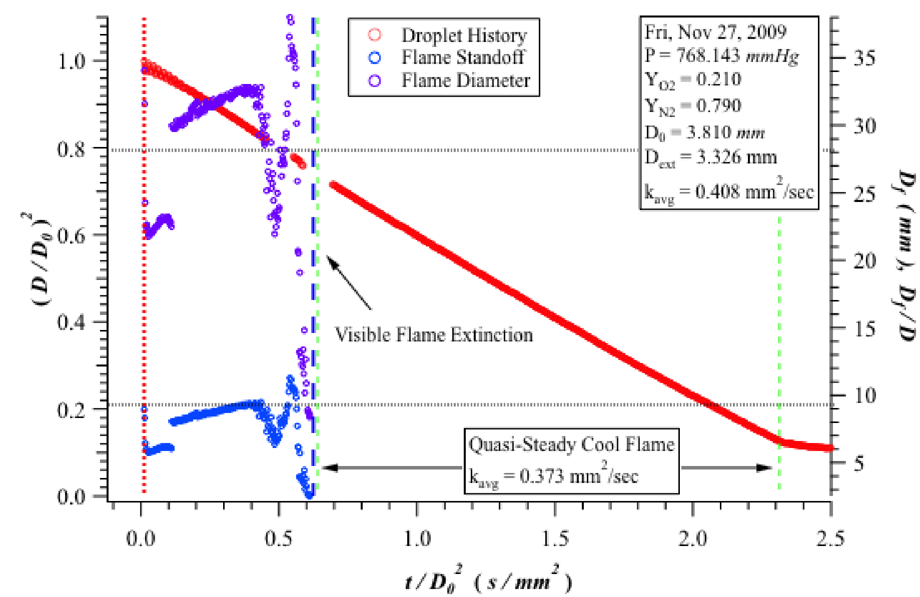
Limiting Oxygen Index (LOI) Tests



LOI's typically lower than in 1-g

NFPA standard for portable CO2 extinguishers not conservative enough for enriched O2 (e.g., EVA pre-breathe), microgravity environment

Cool Flame Results



Gaseous Diffusion Flames (MSG)

Smoke Point in Co-flow Experiment (SPICE) – 2010

Soot control remains one of the major unsolved issues in combustion. Soot:

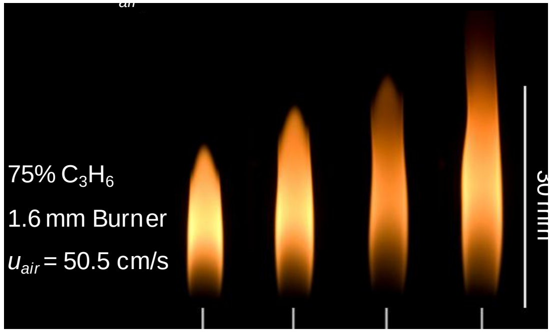
- Is the dominant source of radiant heat
- Is a major pollutant and health risk
- Is desired in some combustors and not in others.

Soot emission in flames is the result of the interplay of soot formation and soot oxidation kinetics. The smoke point is a long standing measure of the sooting propensity of fuels used in fuel selection and flame radiation modeling.

Initially deemed not possible in reduced gravity, the smoke point has been found to be substantially different in reduced gravity.

SPICE has extended this observation to consider the impact of the coflowing air stream on the smoke point

SPICE Experiment Assembly



Still images showing the onset of the smoke point

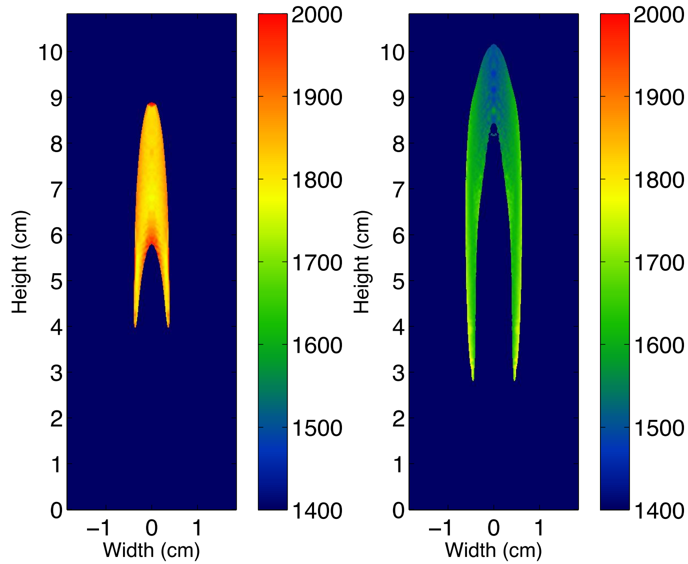
ISS Results Gaseous Diffusion Flames (MSG)

Structure & Liftoff In Combustion Experiment (SLICE) – 2012

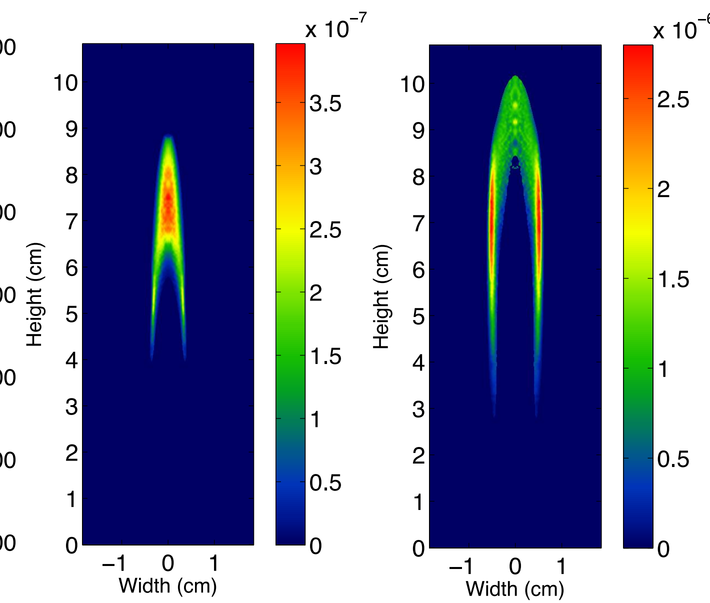
- **Study of flame structure and stability limits.**
  - Support the ACME Coflow Laminar Diffusion Flame (CLD Flame) experiment
  - Enables validation of combustion models over a wider parameter range.
- **Preliminary results**
  - Lower flame temperatures
  - Dramatically increased soot concentrations in microgravity
  - Stability data indicates that the 0g/1g difference in forced air flow at liftoff is comparable to the buoyant velocity in the 1g flames

1g 0g

100% CH_4 flame



1g Temperature 0g



1g 0g

Soot Volume Fraction

ISS Results Solid Fuel Combustion-Material Flammability

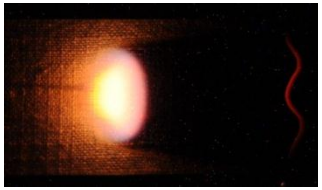
BASS in MSG
Don Pettit running BASS

The **Burning and Suppression of Solids Experiment (BASS) – 2012 in process now**

Recent Results:

Material Flammability: Results to date indicate that NASA-STD 6001 Test 1 is not conservative, and materials can burn at lower oxygen levels in microgravity than on Earth.

Extinguishment: Results to date indicate that local application of suppressant is not adequate. The local jet entrains air and sustains the flame even when the ambient air flow is turned off.



Nomex III burning in BASS in air. This material will not burn in air on earth.

Spherical PMMA sample in BASS. N2 Jet does not extinguish flame, only blows out stagnation region. Wake region continues to burn.

N_2 flow makes candle flame longer, it does not put it out.

Image analysis

Relevance/Impact:

Spacecraft fires are a significant risk factor for human exploration.

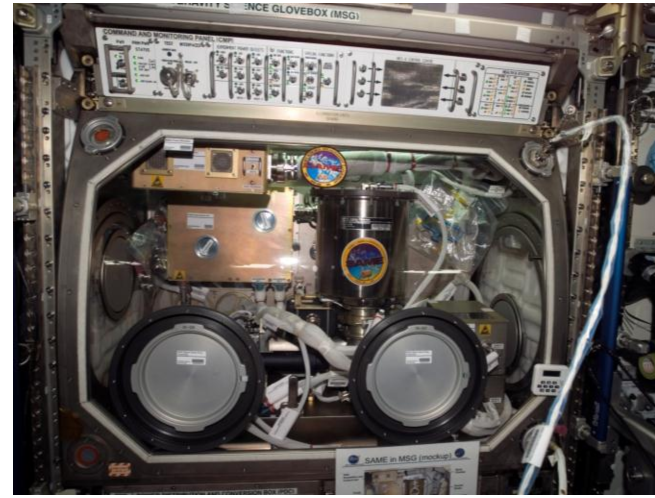
Understanding material flammability and suppression in actual spacecraft environments is needed

Long-duration microgravity data is needed for all but the thinnest films.

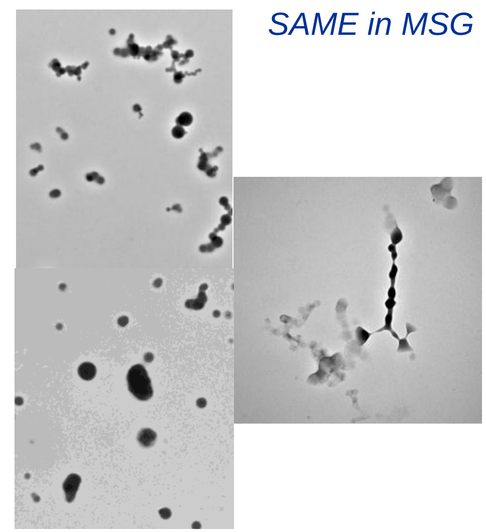
ISS Results Spacecraft Fire Safety

The Smoke Aerosol Measurement Experiment (SAME) 2007 & 2010

- Spacecraft fire is a recognized risk however there has been limited study of fires in 0-gravity.
- Current fire detection and suppression systems are consequently based on 1-g experience not 0-g fires
- The reduced airflow seen in low-gravity enhances the smoke residence time near the source, enabling enhanced particle growth.
- SAME pyrolyzed 5 materials commonly found in spacecraft and made measurements of the particle size distribution
- Smoke particles produced in low gravity are typically twice the size on those produced in normal gravity however the overall morphologies are similar.
- These measurements will enable rational design of spacecraft smoke detectors.

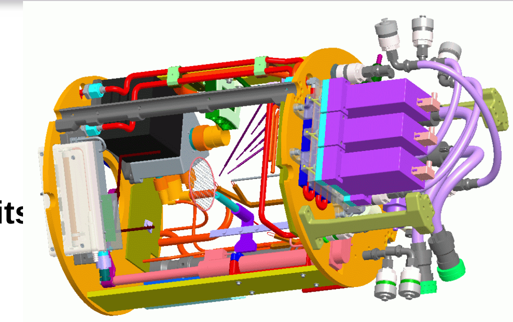


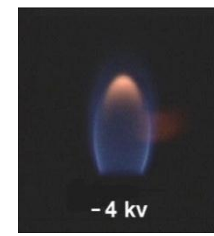
SAME in MSG

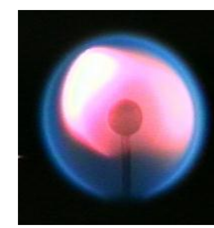


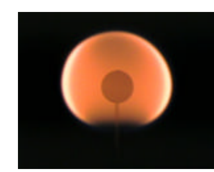
TEM photos of smoke particles from different materials (clockwise from the top: Pyrell, Teflon and Cotton) Horizontal dimension of images ~ 2 microns

Advanced Combustion via Microgravity Experiments (ACME)









Objectives:

- **Exploit 1-D geometry to study**
  - **Soot inception and growth**
  - **combustion structure and stability near flammability limits**
  - **emission reduction through nitrogen exchange**
- **Exploit low-g environment to study**
  - **Flame structure under lifted conditions**
  - **combustion stability enhancements via an electric field**
  - **Flammability Limits on solid fuels through planar burner analogy**

Relevance/Impact:

- **Soot and pollutant control through “designed flames”**
- **Verified computational models - enable the design of high efficiency, low emission combustors operating at near-limit conditions**
- **Reduced design costs due to improved capabilities to numerically simulate combustion processes**

Development Approach:

- **Multi-user, re-usable CIR Insert**

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Flammability Assessment of Materials for Exploration (FLAME)

Objective:

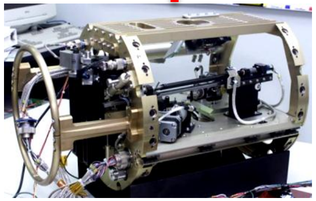
- To study and characterize ignition and flammability of solid spacecraft materials in practical geometries and realistic atmospheric conditions

Relevance/Impact:

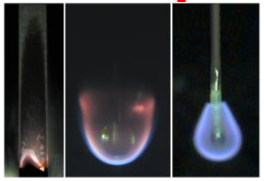
- Enable improved selection of cabin materials and validate NASA materials-flammability selection protocols for low-gravity fires
- Improve understanding of early fire growth behavior
- Validate material flammability numerical models
- Determine optimal suppression techniques for burning materials by diluents, flow reduction, and venting

Development Approach:

- Develop FLAME facility (CIR or MSG insert) to support multiple solid-material combustion and fire suppression studies
- Utilize Combustion Integrated Rack (CIR) or Microgravity Science Glovebox (MSG)



CIR Insert – FLEX (Similar to anticipated FLAME insert)



Flat, Spherical, and Cylindrical samples (L to R) burning in 1-g

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Supercritical Water Oxidation (SCWO) - DECLIC

Supercritical Water Mixture (SCWM) Experiment - planned for Spring of 2013

Relevance/Impact:

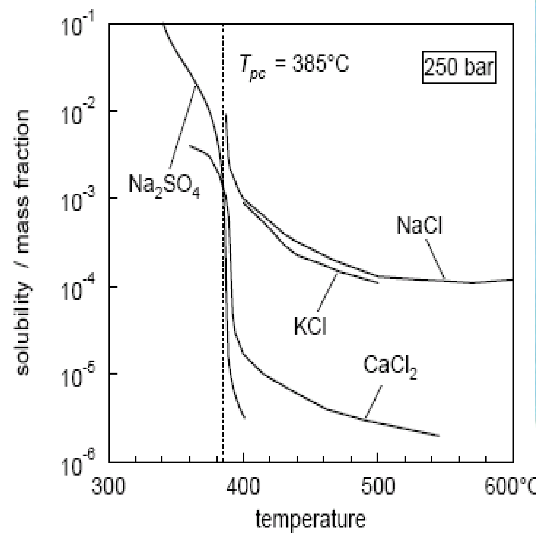
- Supercritical Water Oxidation (SCWO) … a combustion regime occurring in water at temperatures and pressures in excess of water's critical point (Tc = 374° C, P = 218 atm)
- Benefits from this oxidation regime …
  - single phase … reactions are not slowed by inter-phase transport
  - behaves like a dense gas … high diffusion rates, very rapid reaction rates
  - organic materials and gases (e.g., O_2) are highly soluble in supercritical water
- Largest technological hurdle … fouling / corrosion from precipitated salts

Science Objectives:

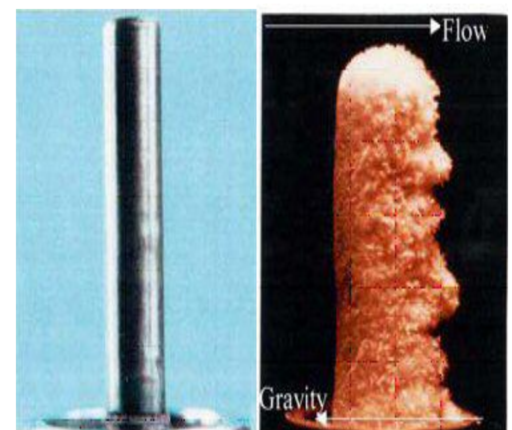
- SCWM experiment will be used to develop mitigation strategies to deal with fouling and corrosion caused by salt deposits
  - Quantify critical point for salt/water mixture
  - Determine the onset of precipitation
  - Characterize the transport processes of the precipitate

Approach:

- **SCWM** uses a refurbished insert, High Temperature Insert (HTI-R) in DECLIC
- Test cell filled with water/salt solution (0.5%-w Na_2SO_4)



Solubility curves of salts in trans-critical water



before

after

steel rod, heated to above Tc … both **before** and **after** 15 minutes of exposure

Spacecraft Fire Safety Demonstration

- Most U.S. agencies responsible for inhabited structures and transportation systems conduct full-scale fire tests to address gaps in fire safety knowledge and prove equipment and protocols.
- NASA has been unable to conduct such tests owing to risk to the crew.
- Unmanned vehicles provide a new opportunity.
- Demonstration of this operational concept could allow future experiments to investigate additional fire safety technologies and protocols or in unrelated areas.

<u>Experiment Objective:</u>

Determine the fate of a large-scale microgravity fire

1. Spread rate, mass consumption, and heat release
   - *Is there a limiting size in microgravity?*
2. Confirm that low-g flammability limits are less than those in normal gravity
   - *Are drop tower results correct?*

FAA full scale aircraft test

Controlled burns of structures

Naval Research Laboratory Ex-USS Shadwell

ESA's ATV approaching the ISS

Orbital Science's Cygnus approaching ISS

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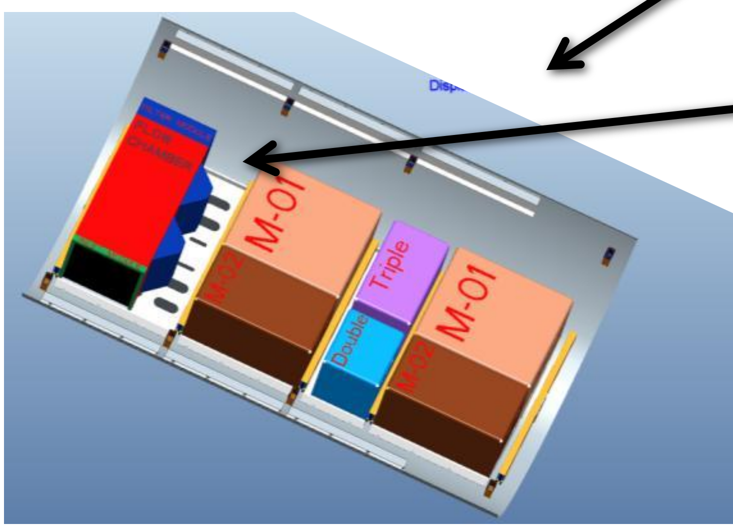
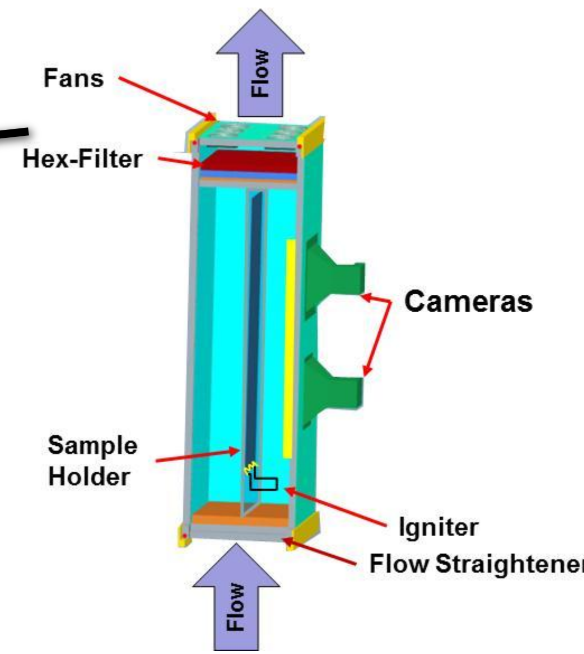
Mission Concept

Cygnus approaching ISS

Unpack cargo, reload with trash

Proposed location of the SFS Demo experiment (back of vehicle)





Conclusions

- Microgravity Combustion research has had significant impact on the combustion discipline and can be expected to continue to make strong contributions.
- Research directions in spacecraft fire safety have promise to significantly improve vehicle safety
- The microgravity environment continues to be a critical resource for improved understanding of combustion phenomena.
- The combustion discipline has been very successful in utilizing low gravity to advance the field and is anxious to seek further opportunities.